THE INTERPRETATION OF THE INSTRUMENTED CHARPY TEST

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SUMMARY

The Charpy impact test has the virtue that the test piece is small. Charpy specimens may, therefore, be irradiated in a nuclear reactor and subsequently removed and tested to monitor the irradiation-induced changes of toughness of the pressure vessel steel. However, the interpretation of the test results presents problems. Historically, measurements of Charpy energy have been used for quality control purposes only, or have been correlated with in-service failures: it has not been possible to determine a fundamental material property from this type of test.

Recently, one of the present authors described a method by which, for below yield behaviour, the dynamic initiation toughness (K_{ICd}) may be determined from an instrumented Charpy test, on a modified specimen, in which the variation with time of the striker nose load is measured. The modified specimen has side grooves and is fatigue cracked at the root of the notch. It is possible, albeit difficult, to measure the variation with time of the crack extension by applying conducting paint grids to the surface of the specimen. Without such records it is difficult to pinpoint the instant of fracture initiation. The method by which K_{ICd} is determined from the experimental readings is based on a simplified analysis of an idealised model of the striker/specimen/abutment system.

The present authors have now developed a transient dynamic finite element computer code specifically for crack propagation studies. This paper describes the application of the code to the analysis of the modified Charpy tests. There were two objectives; the first was to obtain a greater understanding of the mechanics of the Charpy test and the second was to explore the possibility of obtaining a fundamental material property from the test.

The output from the code includes the time-dependent displacement, strain and stress fields, the variation with time of the force on the striker nose, the crack initiation time and the crack extension/time relationship. The paper includes representative experimental and computed results for two materials, bisphenol-A polycarbonate and a mild steel tested at low temperature. The computer predictions were "tuned" to the experimental results by adjustment of parameters representing (i) the initial bluntness of the crack, (ii) the dynamic initiation toughness (iii) the velocity-dependent dynamic toughness apropriate to a running crack (K_D) and (iv) the striker/specimen contact stiffness.

The resulting agreement between the computer predictions and the experimental measurements is most encouraging, giving confidence in the ability of the model to predict the behaviour of the Charpy specimen in greater detail than was possible hitherto. For example, in the case of a comparatively brittle specimen, the present model predicts oscillations of the central bending moment which the simpler model does not predict.

The first objective has, therefore, been attained. So far as the second objective is concerned, the authors have obtained the material properties by an iterative process in which the parameters of the model have been adjusted until the predictions of the model match the experimental measurements. The paper includes results so obtained and comparative results obtained from the same experimental measurements by the method based on the simple model.

1. Introduction

The Charpy impact test has the virtue that the test piece is small. Charpy specimens, may, therefore, be irradiated in a nuclear reactor and subsequently removed and tested to monitor the irradiation-induced changes of toughness of the pressure vessel steel. However, the interpretation of the test presents problems. Historically, measurements of Charpy energy have therefore been used for quality control purposes only, or have been correlated with in-service failures: it has not been possible to determine a fundamental material property from this type of test.

Recently, Turner et al [1] described a method by which, for behaviour below general yield, the dynamic initiation toughness may be determined from an instrumented Charpy test in which the variation with time of the striker nose load is measured. The interpretation of the test is facilitated by measurement of the variation of crack length with time by use of conductive paint grids deposited on the sides of the specimen. This enables a more accurate determination of the time at which the crack begins to propagate. The method of analysis is based on a simple model of the striker/specimen/abutment system.

The present authors have now developed a transient dynamic finite element computer code specifically for elastic crack propagation studies. This paper describes the code and its application to the analysis of the Charpy test. There were two objectives: the first was to obtain a greater understanding of the mechanics of the Charpy test and the second was to explore the possibility of obtaining a fundamental material property from the test.

The output from the code includes the time-dependent displacement, strain and stress fields, the variation with time of the force on the striker nose, and the crack extension/time relationship. The paper includes representative experimental and computed results for two materials, bisphenol-A polycarbonate and a carbon-manganese steel tested at various temperatures. The computer predictions were "tuned" to the experimental results by adjustment of parameters representing (i) the dynamic initiation toughness, including the effect of initial bluntness of the notch, (ii) the dynamic toughness appropriate to a running crack, which, in principle, may be assumed to be velocity-dependent and (iii) the striker/specimen contact stiffness.

The resulting agreement is most encouraging, giving confidence in the ability of the model to predict brittle behaviour of a Charpy specimen in great detail. Values of the dynamic initiation toughness and the dynamic toughness appropriate to a running crack have been obtained. The values of dynamic initiation toughness have been compared with values obtained from the same experimental results using the simpler method of analysis.

2. Transient Dynamic Computer Programme

The finite element discretisation of a continuum leads to the well-known matrix form of the equation of motion [2] :

$$[K]\ \{\delta\} + [C]\ \{\dot{\delta}\} + [M]\ \{\ddot{\delta}\} = \{F(t)\} \qquad (1)$$

where

$[K]$ = stiffness matrix

$[C]$ = viscosity matrix

$[M]$ = mass matrix

$\{\delta\}$ = displacement vector

$\{F(t)\}$ = force vector

and where t denotes time and the dot indicates the derivative with respect to time. In the analyses described in this paper, the material viscosity was neglected. The "lumped" mass matrix was used, reducing the computing time by about 80%, with about 4% loss of accuracy.

The computer programme integrates eq. (1) stepwise in time, using a method similar to that described by Hitchins and Dance [3]. The accelerations at sequential time points are assumed to be related by a Lagrangian polynomial of the second order. Thus the displacements and velocities at time $t+\Delta$ are obtained from those at t and $t-\Delta$ by the following equation:

$$\begin{pmatrix} \{\delta_+\} \\ \{\dot{\delta}_+\} \end{pmatrix} = \begin{pmatrix} [I] & \Delta[I] \\ [0] & [I] \end{pmatrix} \begin{pmatrix} \{\delta_o\} \\ \{\dot{\delta}_o\} \end{pmatrix} + \begin{pmatrix} -\frac{\Delta^2}{24}[I] & \frac{5\Delta^2}{12}[I] & \frac{\Delta^2}{8}[I] \\ -\frac{\Delta^2}{12}[I] & \frac{2\Delta}{3}[I] & \frac{5\Delta}{12}[I] \end{pmatrix} \begin{pmatrix} \{\delta_-\} \\ \{\delta_o\} \\ \{\ddot{\delta}_+\} \end{pmatrix} \tag{2}$$

The subscripts +,o,- denote the values at times $t+\Delta$, t, $t-\Delta$ respectively. $[I]$ denotes unit matrix and Δ is the time interval. To advance the solution of eq. (1) from time t to time $t+\Delta$, the estimated accelerations at time $t+\Delta$, $\{\ddot{\delta}_+\}$, are substituted into eq. (2) to obtain a first estimate of the displacements $\{\delta_+\}$ and velocities $\{\dot{\delta}_+\}$ at $t+\Delta$. Eq. (1) is then used to obtain a better estimate of the accelerations $\{\ddot{\delta}_+\}$ and the iteration continued until adequate convergence is obtained. The solution is then advanced by a further time step. The length of the time step is taken to be

$$\Delta \leqslant s/5C_L \tag{3}$$

where s = smallest finite element side length

C_L = dilational wave speed

In an analysis of a specimen or component in which an unstable crack is propagating, it is necessary to introduce a crack extension criterion. There are two obvious possibilities, which have been shown to be equivalent. The first was used by Hahn et al [4] and by Kanninen [5], who computed the dynamic energy release rate G_D, given by

$$G_D = \frac{dW}{da} - \left(\frac{dU}{da} + \frac{dT}{da}\right) \tag{4}$$

where

W = work done by externally-applied forces

U = total strain energy

T = total kinetic energy

a = crack length

They postulated that crack extension will occur when G_D equals the dynamic toughness of the material, R, which is, in general, a function of the crack speed $\dot{a}$.

In the analyses described in the present paper an alternative criterion was used. One half of the specimen was modelled, using two-dimensional triangular linear-displacement plane strain elements (see Fig.1). The nodes on the plane of symmetry of the specimen were constrained by forces acting in the direction normal to the plane of symmetry. It has been shown by Keegstra [6] that, for a given mesh, the force on the crack tip node is proportional to the stress intensity factor K_1. In these analyses, the authors used, as a criterion, the postulate that crack extension will occur when the force on the crack tip node reaches a critical value F_c. This is equivalent to postulating that crack extension will occur when the dynamic stress intensity factor reaches a critical value K_D which is also, in general, a function of the speed of a running crack.

The programme computes the crack speed from the intervals between the release times of adjacent nodes. The crack is assumed to have arrested if the force on the crack tip node does not reach F_c within a reasonable time period measured from the time at which the previous node is released. The time period is chosen, arbitrarily, to correspond to a crack speed of $0.01\ C_L$.

In the linear elastic finite element model, there is no mechanism by which energy may be dissipated. The inclusion of the viscous forces could not adequately represent the localised energy dissipation in the vicinity of the crack tip. To provide an energy sink, therefore, the crack tip node is not instantaneously released when the constraining force reaches F_c, but is "held back" by a force F_b, which reduces linearly with nodal displacement according to the equation

$$F_b = F_c\ (1 - \bar{v}/v_c) \tag{5}$$

where

$$\bar{v} = \frac{1}{t} \int_0^t v(t^*)\,dt^* \tag{6}$$

and

$v(t^*)$ = instantaneous nodal displacement in the direction normal to the plane of symmetry

t^* = time

t = current time

v_c = reference displacement

Thus $\bar{v}$ is a time-averaged displacement in the direction normal to the plane of symmetry. The node therefore does work against the force F_b and energy is thus extracted from the model. Keegstra has shown that the appropriate choice of the reference displacement is

$$v_c = F_c/K_n \tag{7}$$

where K_n is the stiffness of the node in the direction normal to the plane of symmetry.

This method ensures that energy is extracted from the vicinity of the crack tip, thus modelling, in a reasonable way, the dissipation mechanisms which occur in near-brittle crack propagation.

3. Analysis of the Charpy Test

In the Charpy test, in which the mass of the striker greatly exceeds the mass of the specimen, the energy absorbed by the specimen is a small fraction of the kinetic energy of the striker at the instant the striker first contacts the specimen. This is especially true if there is no gross yielding of the specimen before fracture. It is reasonable, therefore, to assume that the striker moves at constant velocity throughout the test. In the finite element model, the striker load is represented by the force in a spring, one end of which moves at a constant velocity equal to the striker velocity, the other end contacts the specimen (see fig.1). The stiffness of the spring represents the combined contact stiffnesses of the striker and the specimen. Thus the force applied to the model, to represent the striker load, is given by

$$\{F_L(t)\} = H(e)k_p \left(\{V\}\ t - \{\delta_s\}\right) \tag{8}$$

where

$$\{V\} = \begin{Bmatrix} V \\ 0 \end{Bmatrix} = \text{striker velocity (assumed constant)}$$

$$\{\delta_s\} = \begin{Bmatrix} u_s \\ 0 \end{Bmatrix} = \text{displacement of struck node}$$

k_p = combined contact stiffness of the striker and the specimen

and H(e) is a step function defined by

$$\begin{aligned} e \geq o\ ;\quad H(e) &= 1 \\ e \leq o\ ;\quad H(e) &= 0 \end{aligned} \tag{9}$$

where

$$e = Vt - u_s \tag{10}$$

Thus e is a measure of the compression of the spring. The inclusion of the step function ensures that when e becomes negative, indicating loss of contact between the striker and the specimen, the striker load $\{F_L(t)\}$ is set to zero. The work done on the specimen by the

$$W = \int_{u_s=o}^{u_{s,max}} F_L(u_s)\,dU_s \tag{11}$$

where the upper limit, $u_{s,max}$, is the displacement of the struck node at the instant that the propagating crack reaches the back face of the specimen. Eq. (11) may be recast, with time t as the independent variable

$$W = \int_{t=o}^{t_{max}} F_L(t)\ \dot{u}_s\ dt \tag{12}$$

This form of the equation was used in the analyses.

The vector of external forces $\{F(t)\}$, which appears in the equation of motion, eq. (1), is given by

$$\{F(t)\} = \{F_L(t)\} + \{F_b\} \tag{13}$$

where $\{F_b\}$ is the vector of "holding back" forces.

The analysis is initiated by setting the striker velocity to an appropriate value and advancing the solution by time steps. The force on the crack tip node is monitored. When the force reaches the critical value and the node is released, attention is focussed on the next node. To model crack bluntness, or an initiation toughness which may be higher than the toughness appropriate to a running crack, a higher critical force may be specified for the node at the tip of the initial crack. The critical force for other nodes may be made to depend on the current crack speed, to model the crack speed dependence of the dynamic toughness. In all cases described in the paper, the analysis was continued until the crack tip reach the back face of the specimen.

4. Analysis of Tests on Glassy Polymers

The computer programme was used to analyse instrumented impact tests conducted by Glover et al [7] on Charpy type specimens machined from bisphenol-A polycarbonate (a glassy polymer). Fig.1 shows the specimen geometry and Table 1 gives the material properties. Glover et al tested specimens having the standard Charpy blunt notch and specimens having sharp notches, but found little difference in the measured toughness. They attributed this result to the presence of sharp cracks in the standard notched specimens, introduced by the machining process. In the present analyses, therefore, the specimens were assumed to have sharp notches as indicated in fig.1: no attempt was made to model geometrically the standard Charpy notch. The experimental measurements included the load on the tip of the striker and the crack extension, each measured as a function of time. The crack extension was measured by the use of conductive paint grids deposited on the sides of the specimen. From the measurements of crack extension against time, the variation of crack speed with crack extension was derived. Fig.2 shows the measured striker load, plotted against time measured from the instant of first impact. The computed striker load is shown on the same figure, also the the computed force on the node at the tip of the initial notch. Fig.3 shows the computed and measured crack speeds plotted against crack extension. Two experimental curves are shown, one derived from measurements on a specimen having the standard Charpy blunt notch, the other derived from measurements on a specimen with a sharp notch. Fig.4 shows computed values of external work done, total strain energy, total kinetic energy and fracture work, all plotted against time from first contact.

In the finite element analyses, the authors used the striker velocity and contact stiffness measured experimentally by Glover and listed in Table 1. The material dynamic toughness, expressed in terms of a critical value of the force, F_c, on the crack-tip node, must be input in order to run the computer programme. (As already stated, the dynamic toughness is, in general, a function of crack speed.) Also, the effect of any bluntness of the initial notch, or initiation toughness, must be represented by increasing the critical force for the node representing the tip of the initial notch by an appropriate factor (the tip factor). Trial values of F_c and the tip factor were input and adjusted until the computed variations of striker load against time and crack speed against crack extension matched the experimental results as closely as possible. The values found to give the best match were $K_D = 2.05\ MN/m^{3/2}$ and tip factor = 1.58. (K_D was taken to be independent of crack speed, an assumption justified by the small range of crack speed.) Thus the initiation toughness, K_Q, which includes any geometric effect (i.e. bluntness) and any true initiation effect, is 2.05 x 1.58 = 3.24 $MN/m^{3/2}$. The results given in figs.2,3 and 4 were obtained by use of these values. Glover et al obtained a value 2.0 $MN/m^{3/2}$ for the dynamic initiation toughness, using a simple method of analysis described by Turner et al [1].

5. Analysis of Tests on Carbon-Manganese Steel

The programme was next used to analyse instrumented impact tests on carbon-manganese steel specimens, also conducted by Glover et al [8]. The specimens were Charpy specimens, modified by the provision of side grooves and by forming a fatigue crack at the root of the notch. The material properties and other data are given in Table 2. Three tests were analysed, covering a range of temperature and, therefore, of toughness, although still within the range for which elastic analysis is appropriate albeit not within the normal limits for plane strain LEFM. The optimum values of K_D and tip factor are listed in Table 2. In these tests, the presence of side grooves prevented the measurement of crack speeds. Thus K_D and the tip factor were chosen to give the best fit to the measured striker force/time relationship. Table 2 also lists the values of dynamic initiation toughness derived by Glover et al using the simple method of analysis. As the crack extention/time relationship was not measured, Glover inferred the time at which crack propagation was initiated from the shape of the striker load record. Table 2 gives initiation times derived by Glover and by the present authors, also the calculated and measured values of the work done by the striker.

Fig.6 shows the computed and measured variations with time of striker load and the load on the node at the tip of the initial crack. Fig.7 shows the computed variations of crack speed with crack extension (measured values are not available) and fig.8 shows the computed energies corresponding to one half of the specimen.

6. Discussion and Conclusions

The agreement between the computer predictions and the experimental measurements is encouraging. The authors conclude that the finite element model represents the main features of the behaviour of an elastic specimen/striker system. In particular, by careful choice of the model parameters, the predicted variations of striker load with time agree remarkably well with the experimental results. The predicted variation of crack speed with crack extension, for the polycarbonate specimen, shows all the features of the experimental result, the predicted curve lying generally between the experimental results from two specimens.

From the computer analysis, a value of the material dynamic toughness, K_D, is obtained (see Table 1). The computer analysis also gives a value for the initiation toughness, K_Q, which includes the true initiation toughness (K_{1Cd}) and any apparent increase of toughness resulting from notch bluntness. This is the toughness which may be compared with the value given by the simpler method of analysis. It may be seen that the finite element model gives a value which exceeds that given by the simpler analysis by about 60% (see Table 1).

The values of initiation toughness of the steel specimens are also higher than the values predicted by the simpler analysis, although the discrepancy is smaller and, for the toughest specimen, is only about 2%.

Although the close agreement may be fortuitous, and further studies must be completed before attempting to draw firm conclusions, these observations suggest that the simple method of analysis may be appropriate to tougher specimens, provided there is only localised yielding and LEFM is applicable. By contrast, as suggested by Glover et al, the simple method seems less appropriate to the analysis of tests in which the specimen fails early in the test. In such tests, the load is highly oscillatory, as may be seen from figs.2 and 5. In fact, there was loss of contact between the striker and specimen in this test.

There are other features of the results which should be noted. The force on the crack-tip node increases monotonically, even when the striker load is highly oscillatory. The nodal force is, therefore, a reasonable crack extension criterion and unlikely to lead to anomolous results due to oscillations. Another interesting feature is the near-uniform low crack speed predicted for the toughest steel specimen (see fig.7). This prediction contrasts with the predictions for the more brittle tests, where the crack speed is initially high. It is interesting to note that, in all analyses, the kinetic energy of the fragments is approximately 50% of the work done by the striker on the specimen. This casts some doubt on methods of analysis in which the toughness is derived simply from the loss of energy of the pendulum. Finally, it is interesting to note that, for the steel specimens, the predicted time to fracture is consistently lower than the value estimated from the striker load measurements. This indicates the importance of using some other method to estimate time to fracture, which is a necessary and sensitive input to the simple analysis [9]. It is ironic that, for these tests, the best agreement is found between the two methods of analysis. Clearly, further study is necessary to a complete understanding.

In conclusion, the finite element model described in this paper can model all significant features of the Charpy test and can be used to obtain toughness values. The computing cost is, however, high, mainly because the model parameters must be adjusted by successive trials to obtain the best fit with the experimental measurements. The finite element model will probably be most useful as a means of checking the validity of simpler methods of determining toughness from instrumented tests. The results described here indicate that the simple method devised by Glover et al underestimates toughness especially for very brittle tests, and is therefore conservative.

7. Acknowledgements

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TABLE 1

PROPERTIES OF BISPHENOL-A POLYCARBONATE

Young's Modulus	$= 2.2 \times 10^3$ MN/m^2
Poisson's Ratio	= 0.345
Striker Velocity (V)	= 5 m/s
Contact Stiffness (k_p)	= 15 MN/m
Test Temperature	= 21°C
K_D (from F.E. Analysis)	= 2.05 MN/m$^{3/2}$
Tip Factor	= 1.58

K_Q

(a) from F.E. Analysis = 3.24 MN/m$^{3/2}$

(b) determined by Glover = 2.00 MN/m$^{3/2}$

TABLE 2

PROPERTIES OF C-Mn STEEL

Young's Modulus	$= 2.1 \times 10^5$ MN/m^2
Poisson's Ratio	= 0.27
Striker Velocity (V)	= 5.25 m/s
Yield Stress	= 524 MN/m^2

Specimen	1	2	3
Test temperature ($^\circ$C)	-70	-40	0
Contact stiffness (k_p) (MN/m)	241	$180 + 15 \times 10^3$ F (F = striker load MN)	
K_D (from F.E. Analysis) (MN/m$^{3/2}$)	38.6	59.4	82.5
Tip factor	1.43	1.43	1.05
K_Q (MN/m$^{3/2}$)			
(a) from F.E. analysis	55.2	84.9	86.6
(b) derived by Glover	48.9	73.8	84.5
Time to fracture (μs)			
(a) from F.E. analysis	22.3	32.0	34.7
(b) estimated by Glover	29.8	43.0	49.3
Work done by Striker (J)			
(a) from F.E. analysis	1.13	1.79	2.43
(b) calculated by Glover	1.03	1.19	2.33
(c) measured by Glover	1.21	1.30	2.22

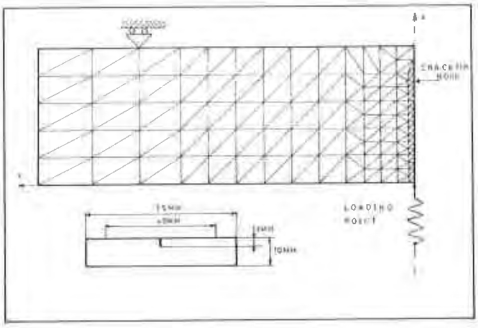

Fig.1 Specimen geometry and finite element mesh

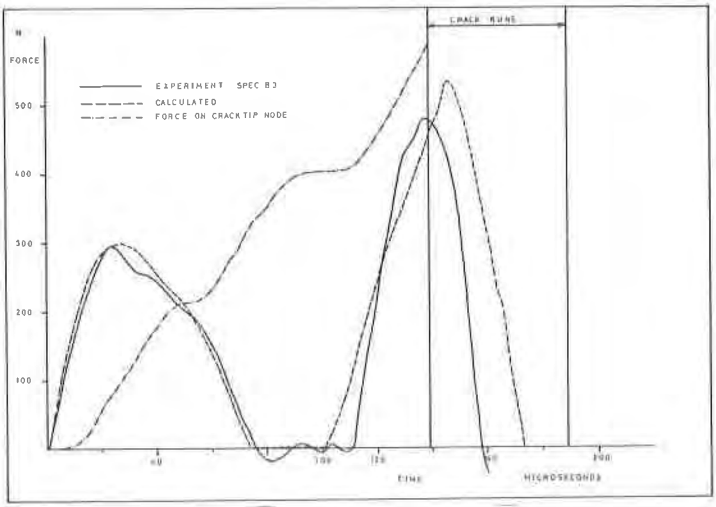

Fig.2 Polycarbonate specimen: computed and measured striker force; force on crack tip node vs time

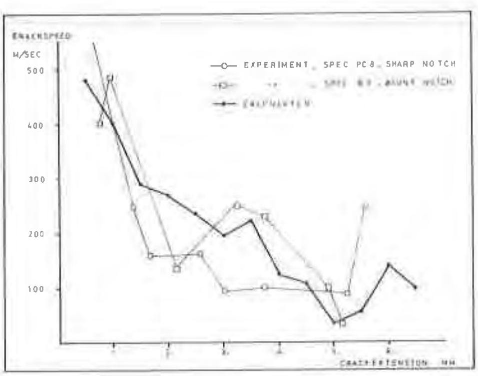

Fig.3 Polycarbonate specimens: computed and measured crack speed vs time

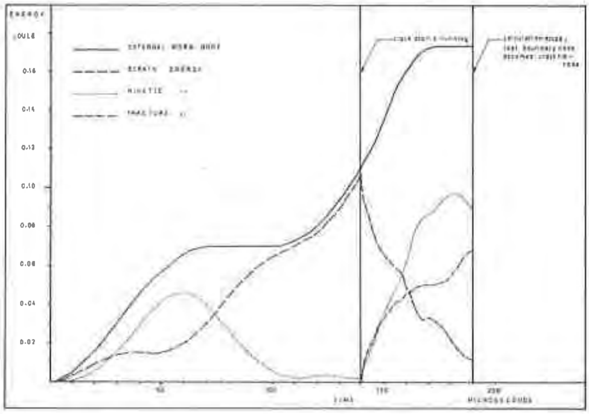

Fig.4 Polycarbonate specimen: computed energies vs time

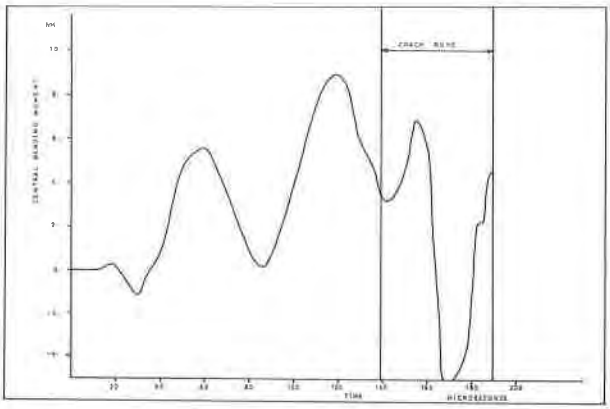

Fig.5 Polycarbonate specimen: computed central bending moment vs time

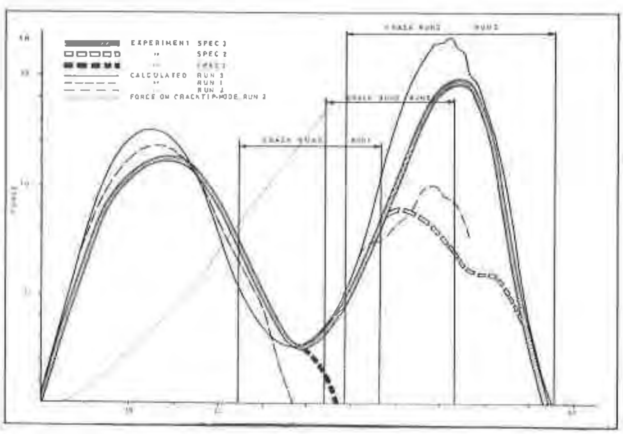

Fig.6 C-Mn steel: computed and measured striker force,; force on crack tip node vs time

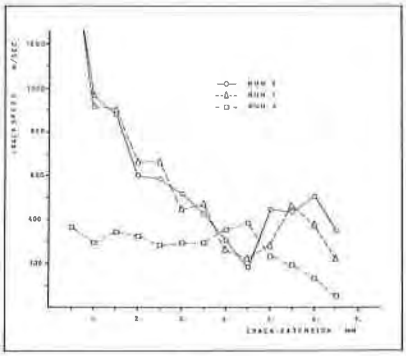

Fig.7 C-Mn steel: computed crack speed vs crack extension

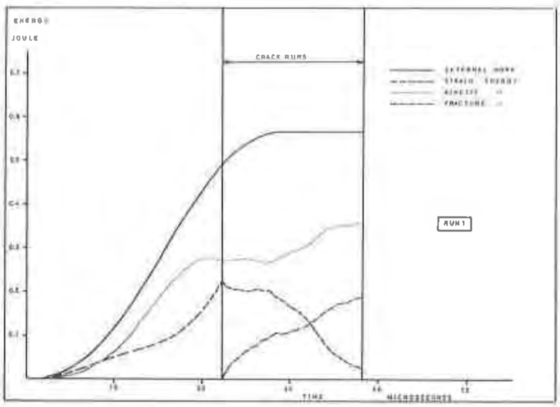

Fig.8 C-Mn steel: computed energies vs time (Run 1)

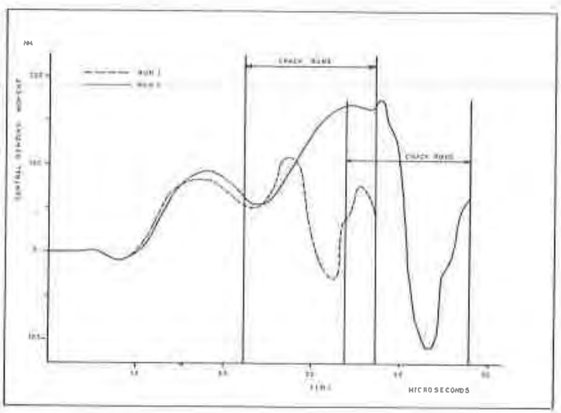

Fig.9 C-Mn steel: computed central bending moment vs time
(Runs 1 and 2)